Cosmology with cosmic voids

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Outline

- **Cosmology Reminder**
- A bit of LSS history
- Void Finding
- Testing cosmology with voids

What do we know of the Universe ?

Cosmology is the study of the Universe, its history, its evolution and its composition at very large scale.

Our knowledge is based in the framework of Einstein's **General Relativity.**

Universe → Isotropic & Homogeneous

→ Invariant by rotation : **No privileged direction !**

→ Invariant by translation: **No privileged position !**

What do we know of the Universe ?

Cosmology is the study of the Universe, its history, its evolution and its composition at very large scale.

Our knowledge is based in the framework of Einstein's **General Relativity.**

Universe → Expanding → At an **accelerated rate !**

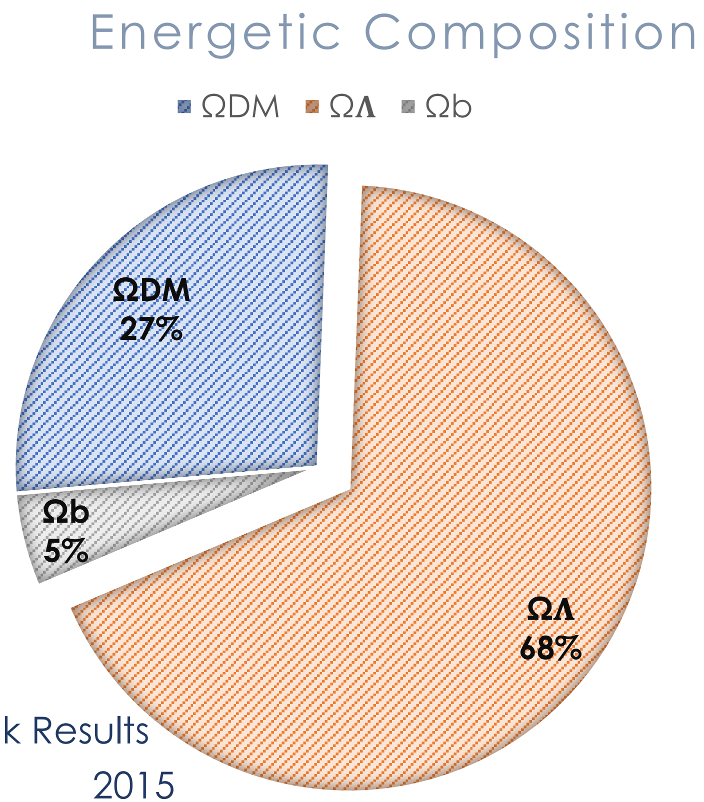
(Riess et al 1998, Perlmutter et al 1998)

What do we know of the Universe ?

Cosmology is the study of the Universe, its history, its evolution and its composition at very large scale.

Our knowledge is based in the framework of Einstein's **General Relativity.**

Universe → Its evolution is related to its composition → Dark energy is responsible for the accelerated expansion



Planck Results 2015

What do we know of the Universe ?

Cosmology is the study of the Universe (very large scale considered). This study relies on Einstein's **General Relativity** theory !

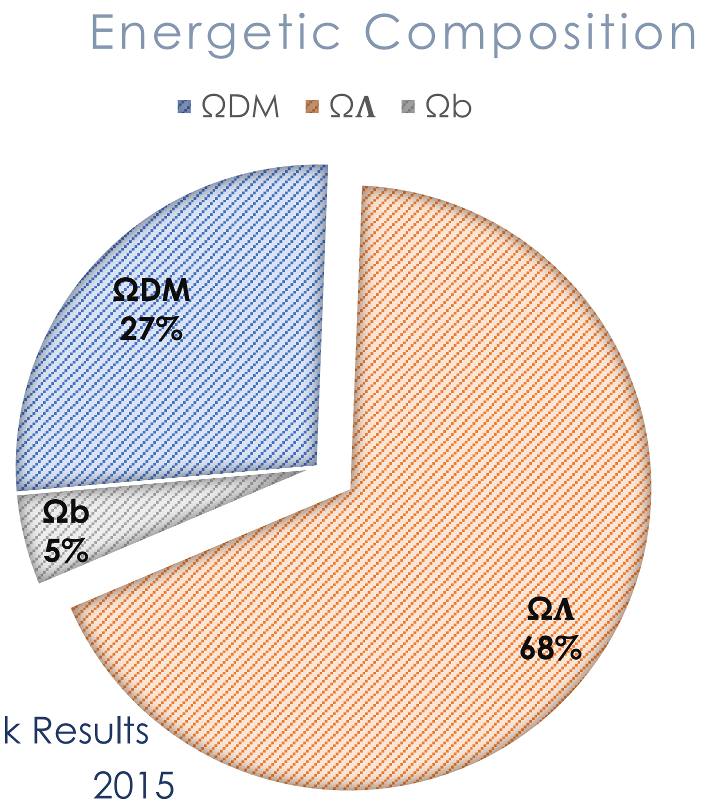
Universe

Flat
$\Omega_k \approx 0$

Isotropic &
Homogeneous

Expanding !
At an **accelerated** rate

Standard Model of Cosmology (ΛCDM)



Planck Results 2015

What are we looking for ?

Two mysteries remains in the framework of ***Λ*CDM** :

- What is dark matter ?
- **What is dark energy ?**

In order to explain that we are looking two ways :

- In the framework of the Standard Model : try to constrain dark energy or/and its equation of state

- Testing General Relativity and looking for a modification of its laws ! → **Modified Gravity**

To resarch those effects, we will look in the Large Scales Structures !

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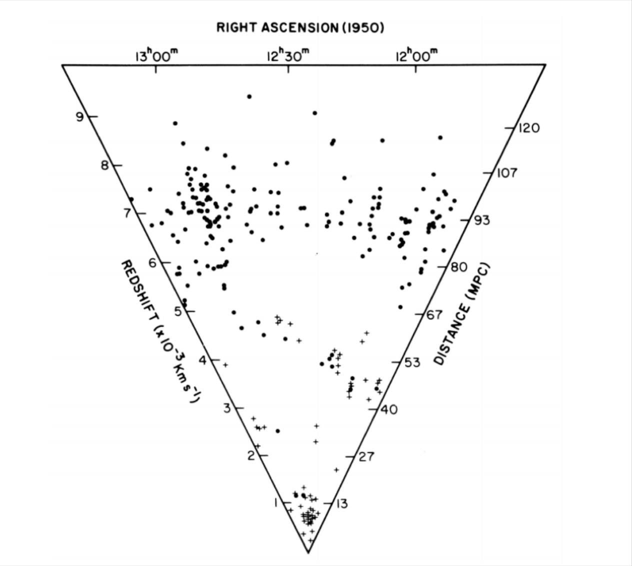
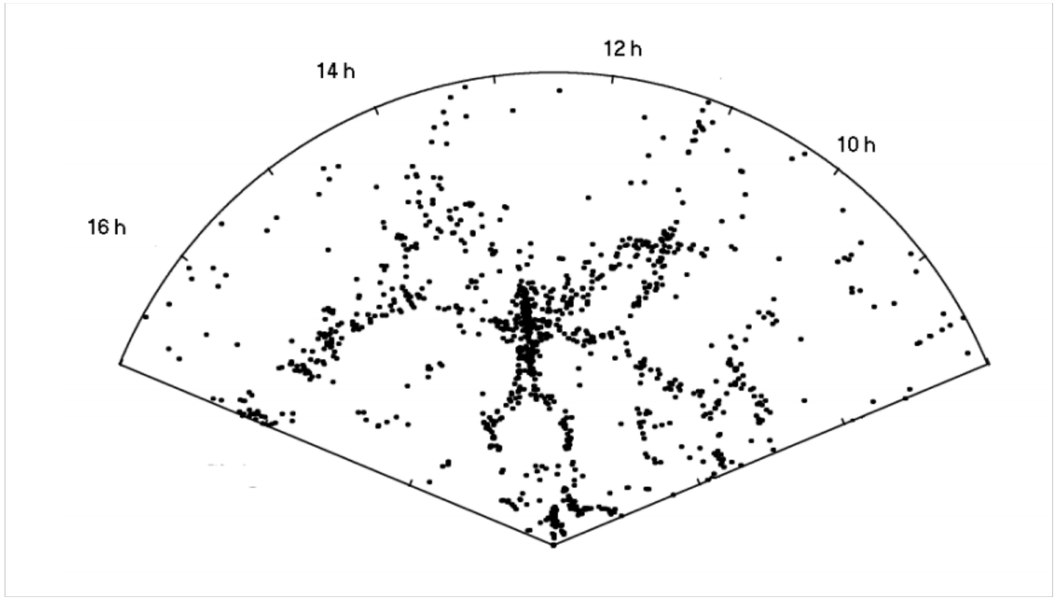
Large Scale Structures

- Large Scale Structures are quite a recent discovery !



First Mention of voids surounding the COMA Supercluster.
Gregory & Thomson **(1978)**



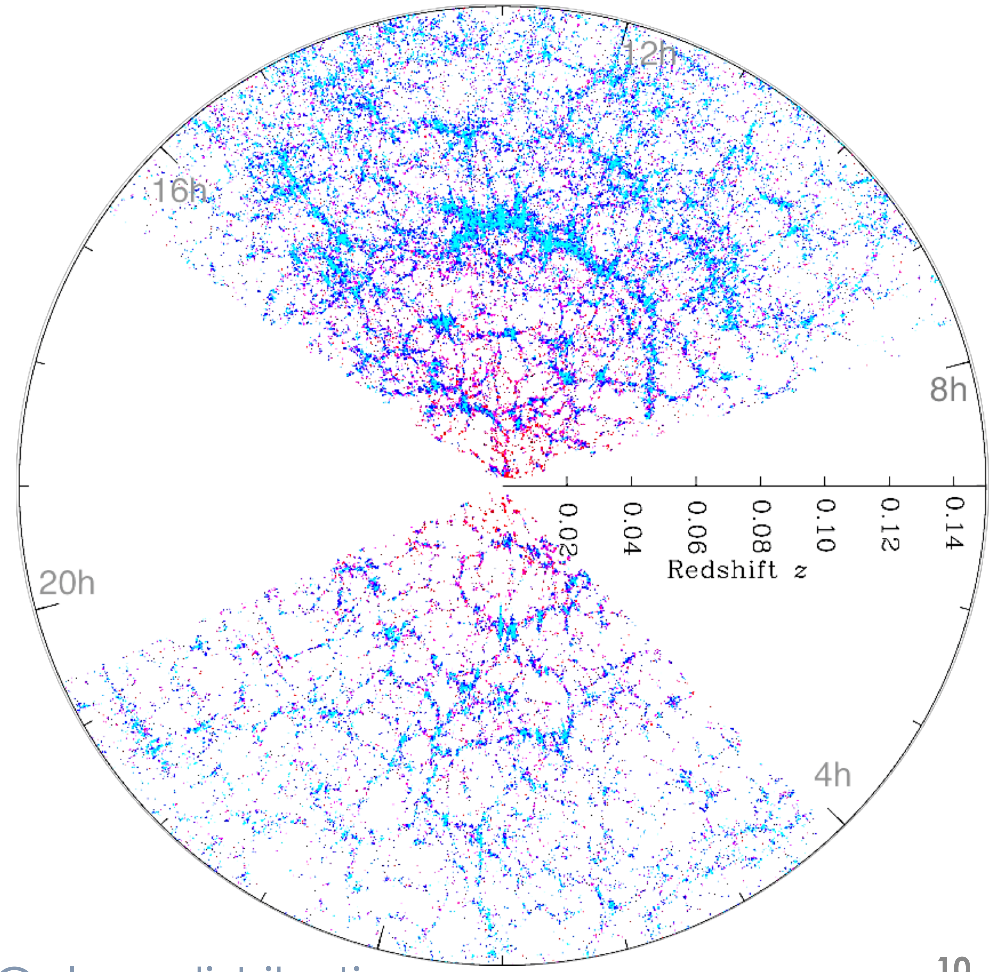
Confirmation of the existence of voids in the cosmic web
de Lapparent et al. **(1986)**

Large Scale Structures

Nowadays, we understand that the LSS :

- Are the remnants of the primordial fluctuations in the early universe.
- Trace the underlying dark matter field
- Are composed as a web of filamentary structures & clusters & **holes**

Voids in the cosmic webs are , by definition, underdensities in the matter field.



SDSS Survey Galaxy distribution

Finding the voids ?

In order to map the large scale structures, **3-D** mapping of the sky is **necessary.**

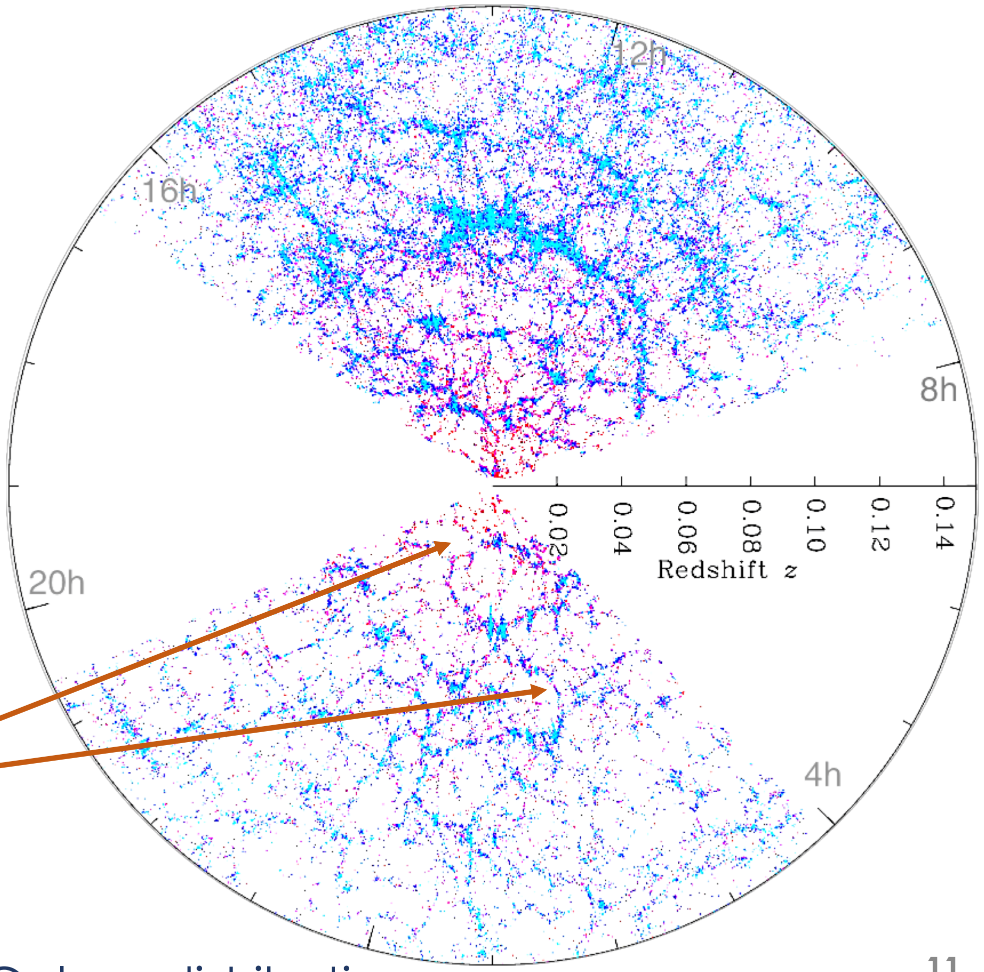
Void science has been rising steadily and the 1st results came out in the 2000's.

A huge volume & a great number of galaxies are needed in order to « observe » them.

→ **How then do we get their properties ?**

It actually depends…

They're here !



SDSS Survey Galaxy distribution

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- **Void Finding (largely inspired from Alice Pisani's courses)**
- Testing cosmology with voids

Void definition

In order to quantify the void, we use algorithms called **Voidfinders**. Their main goals is to extract the voids from a given galaxy distribution.

- Choosing a certain type of voidfinders is not far from choosing a **void definition**.

- The VoidFinder that you choose depends on several factors :
  - The survey features
  - The type of analysis you want to make

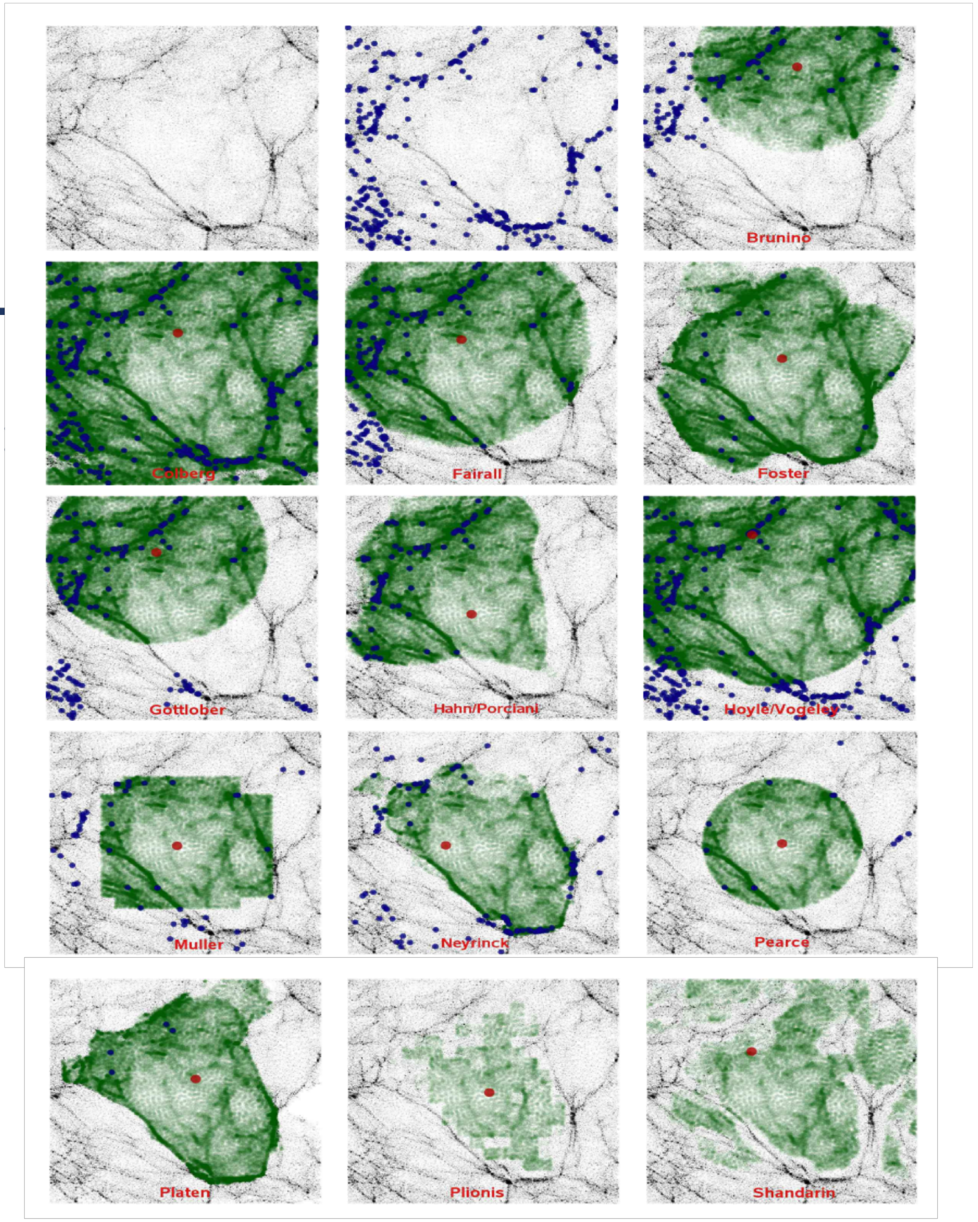
At the end of the day , you want to choose the best void finder in order to maximize the signal you want to measure

Void Finders

- Void finder based on the density field measurement
  - With/Without a shape assumption (spherical)
  - Throught Tesselation of the field

- Localizing only **empty regions** (devoid of matter/galaxy)

There is not « best way » to find voids.



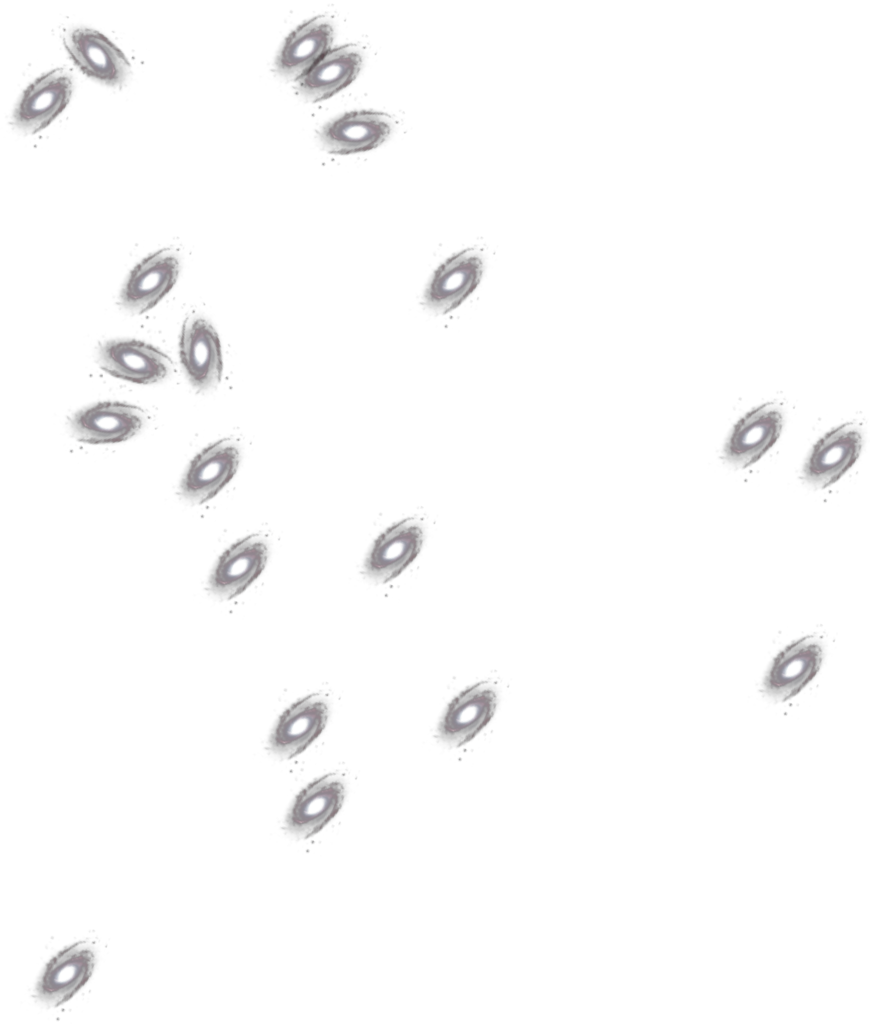
The Aspen–Amsterdam Void Finder Comparison Project (Colberg et al. 2008 , Arxiv: 0803.0918)

VIDE : **V**oid **ID**entification and **E**xamination

Sutter, P. M., Lavaux G., Hamaus N., Pisani A., Wandelt B. D. et al., **Astronomy & Computing** (1406.1191) (ZOBOV, Neyrinck 2008)

- How does it work ? → **With Galaxies position !**

The survey gives us the positions in the sky.



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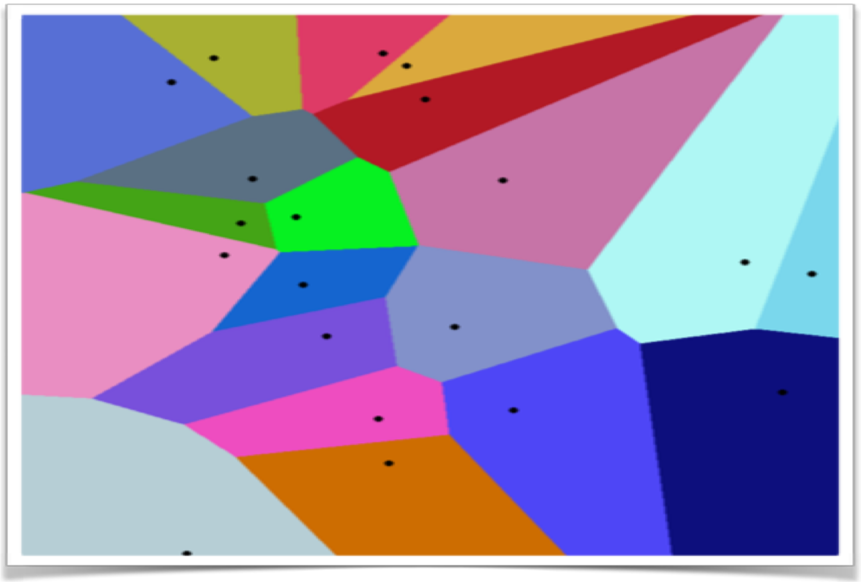
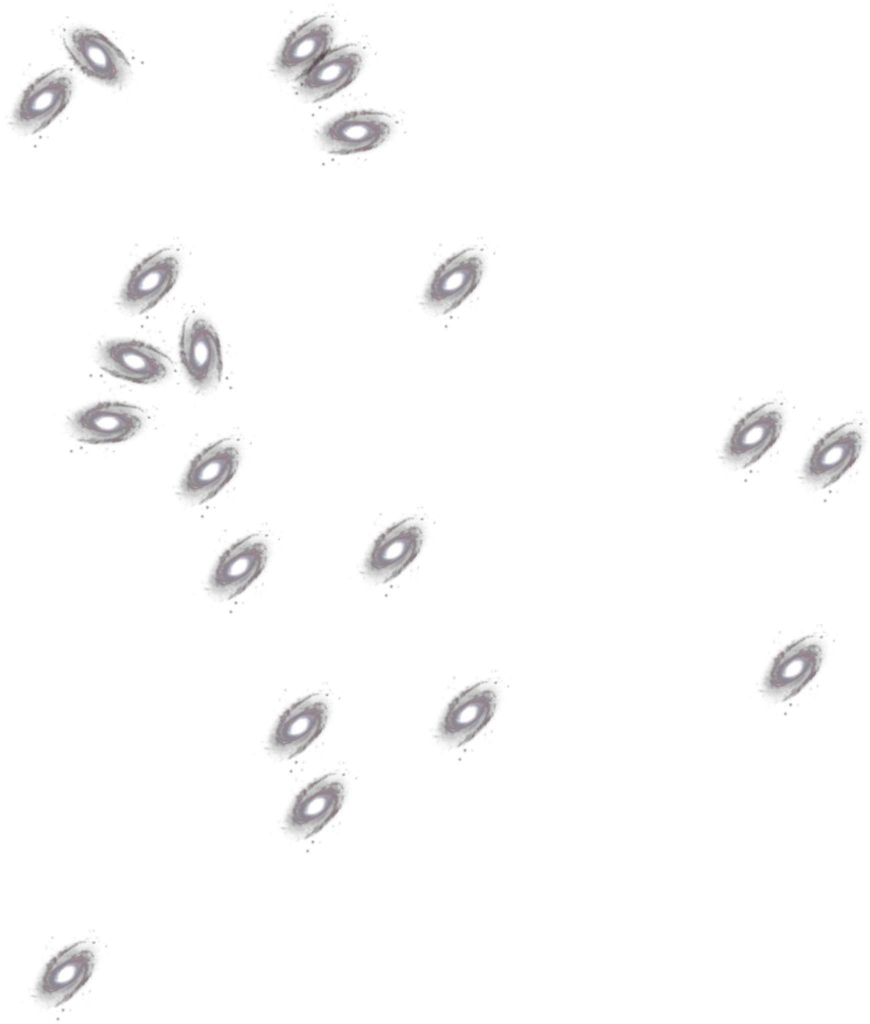
- How does it work ? → **With Galaxies position !**

The survey gives us the positions in the sky.

- Then we practice a Voronoi tessellation.





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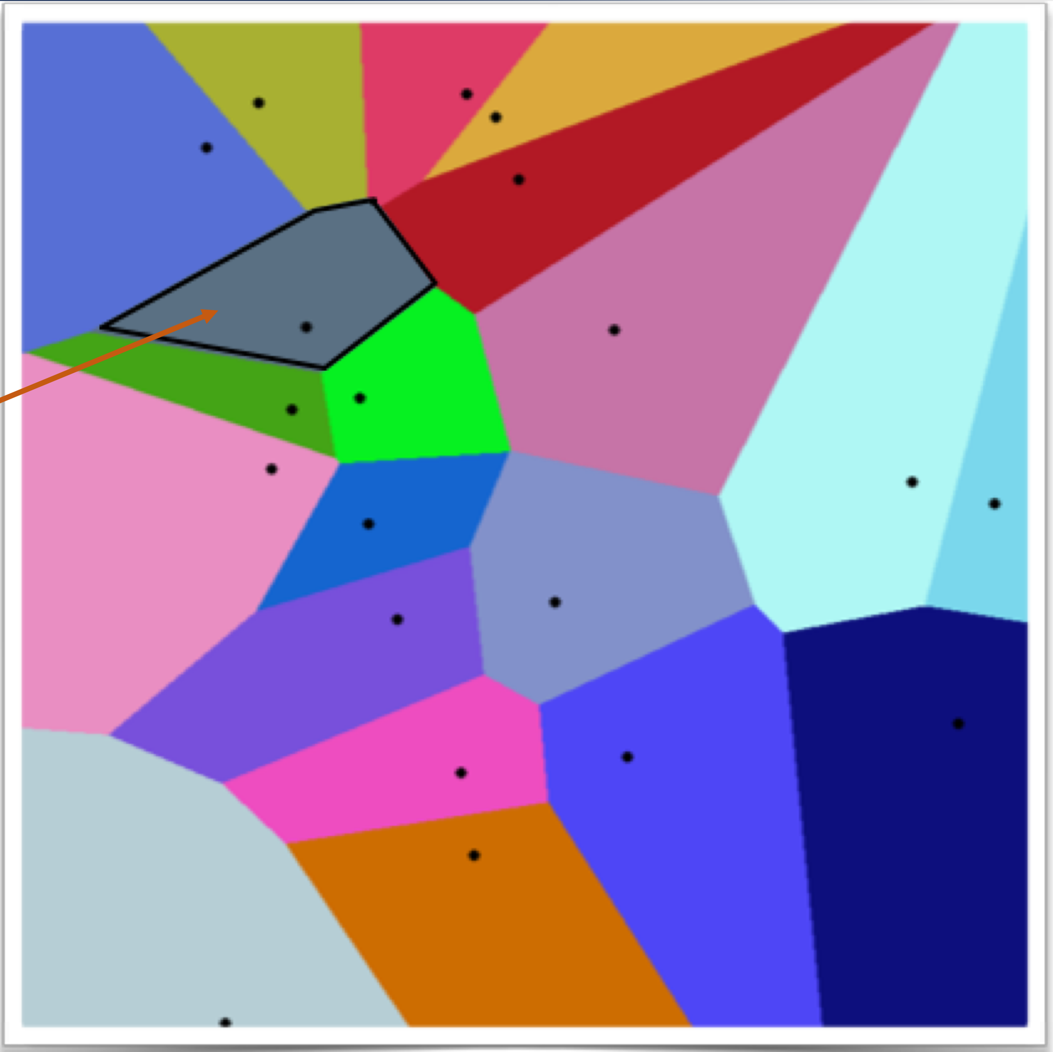
What is a Voronoi Tessellation ? .

Given a set of tracers, the Voronoi Tessellation proceed to a partitionning such that :

- A cell is constructed **around a tracer**.
- The boundaries of the cell are the points that are equidistant to both of the tracers of adjacent cells
- All the points closer to the **tracers considered** are enclosed in the **Voronoi cell.**
- The volume of the cell allows us to have a local density estimation :

$$\rho = \frac{1}{V_{cell}}$$



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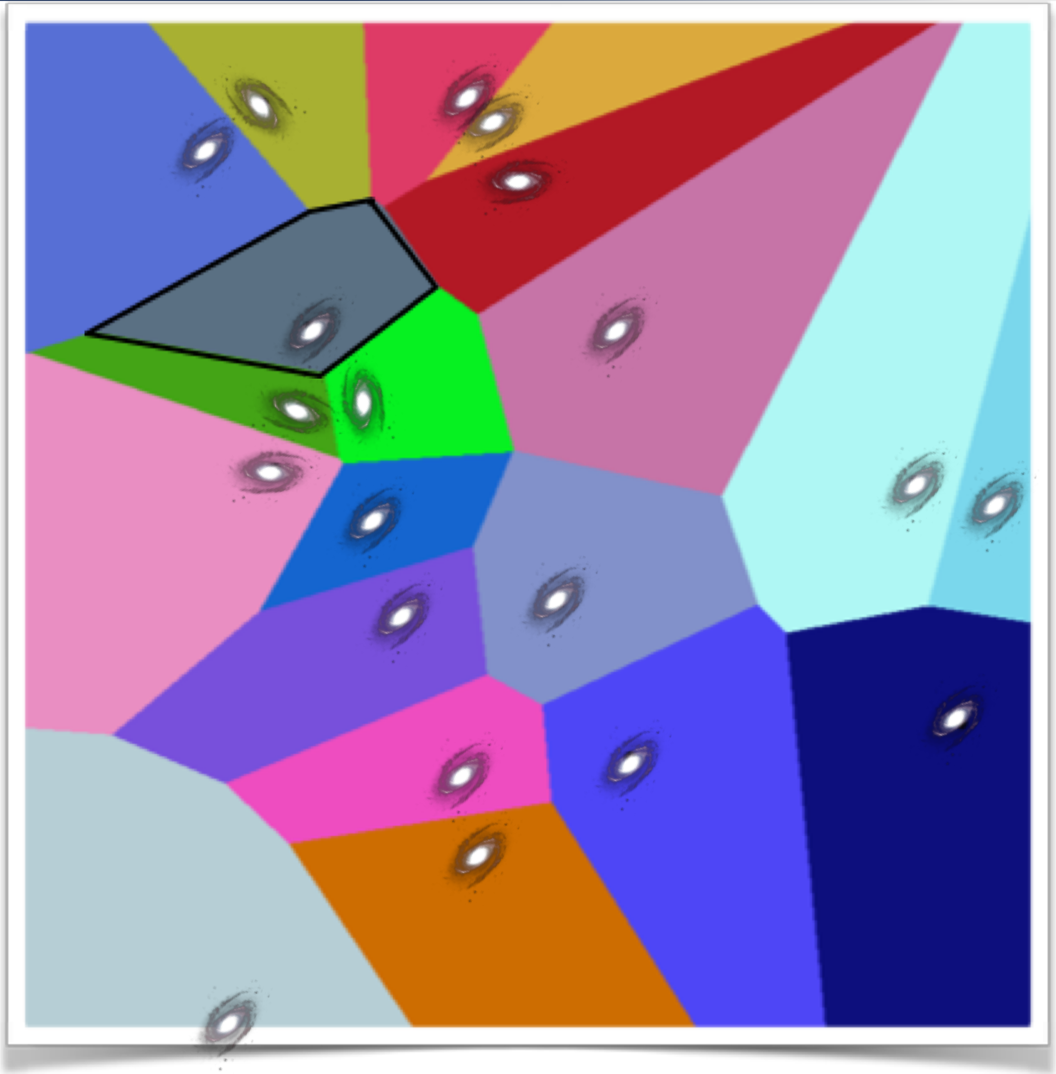
- Applying the Voronoi tessellation allows us to map the galaxy density field, **including :**
  - The density peaks (filaments)
  - The density dips (voids) !

  (Icke & Van de Weygaert , 1987)

Is the work done then ? (No)



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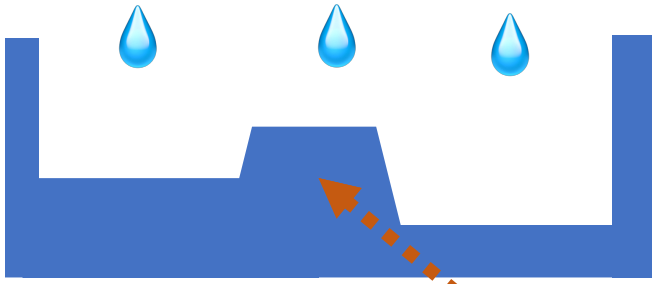
2 low density cells

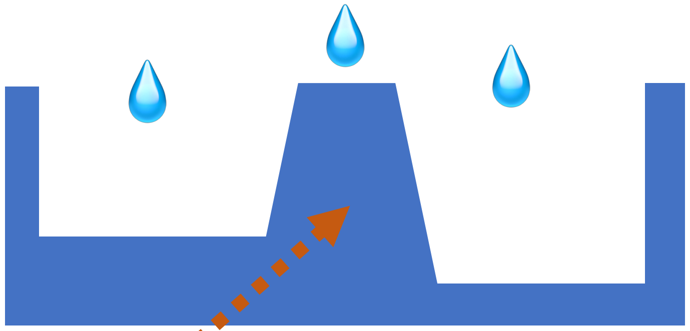


We have to merge the different cells in order to define our voids.

Take 2 adjacent low density cells :

- Compare the density of the wall separating them.

2 low density cells



Separation between 2 Voronoi cells

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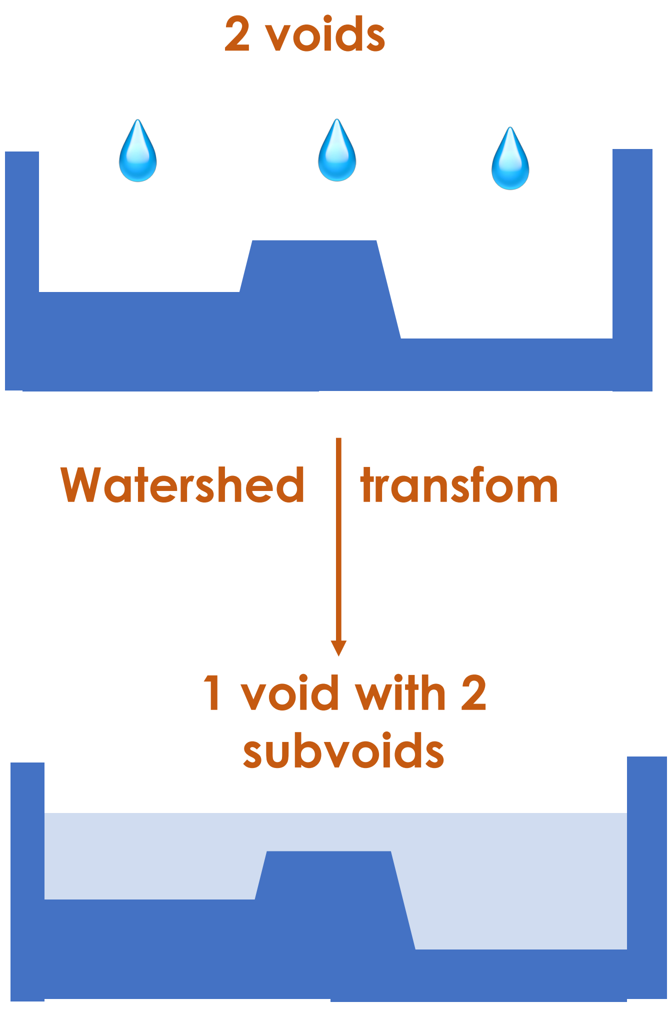
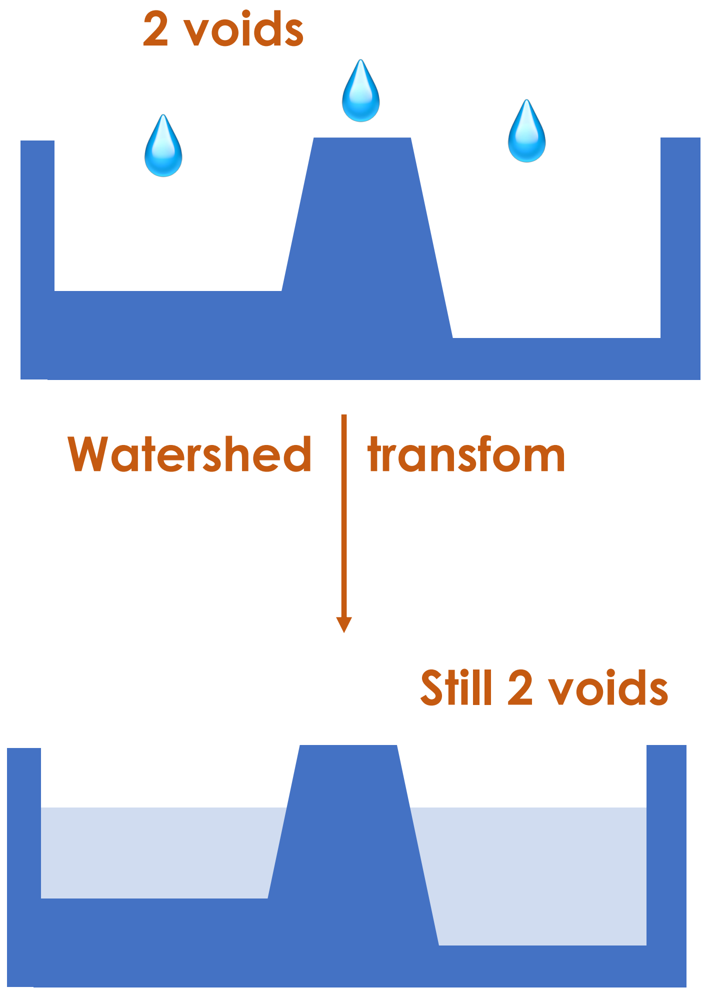


Watershed transform allows us to :

- Merge the different cells into a cluster of low density cells : **a void**
- Capture the hierarchy of the void structures.

(Platen et al. 2007)



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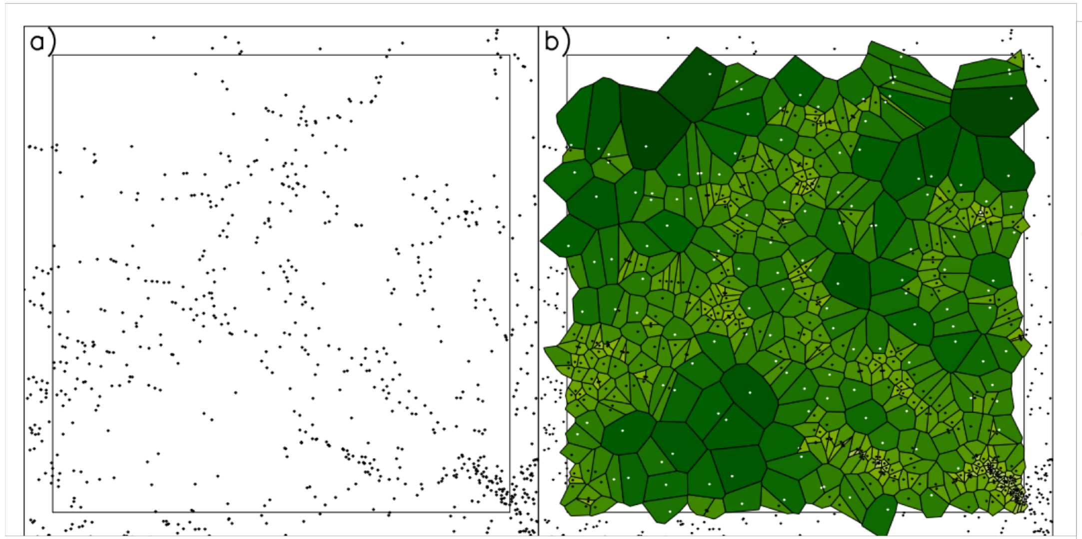

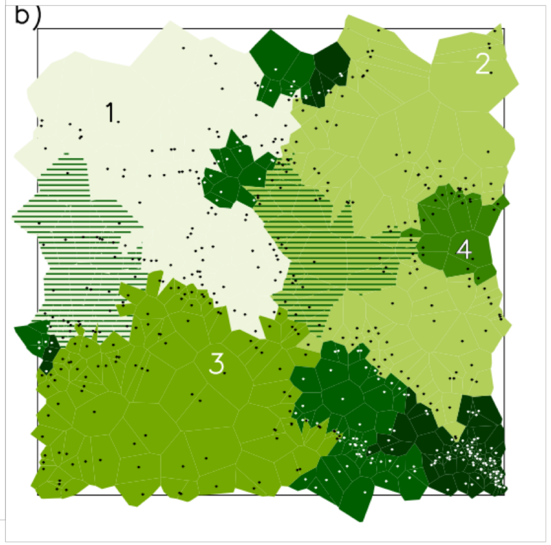

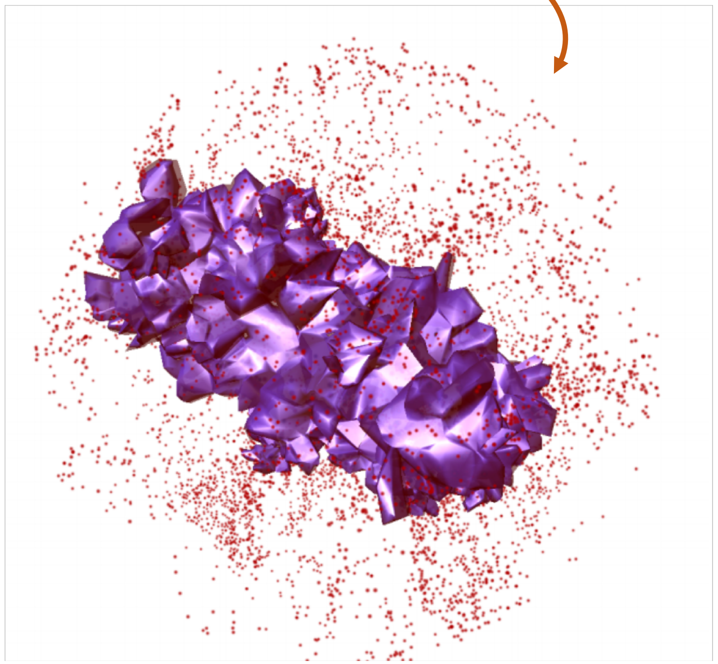

Galaxy distribution

Voronoi tessellation

Watershed Transform

(Neyrinck , 2008)

We obtain :

- The position of the center of the void
- Its radius
- Its member particles **(a void is not necessarily empty)**

(Sutter, 2012b)

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- Cosmology Reminder
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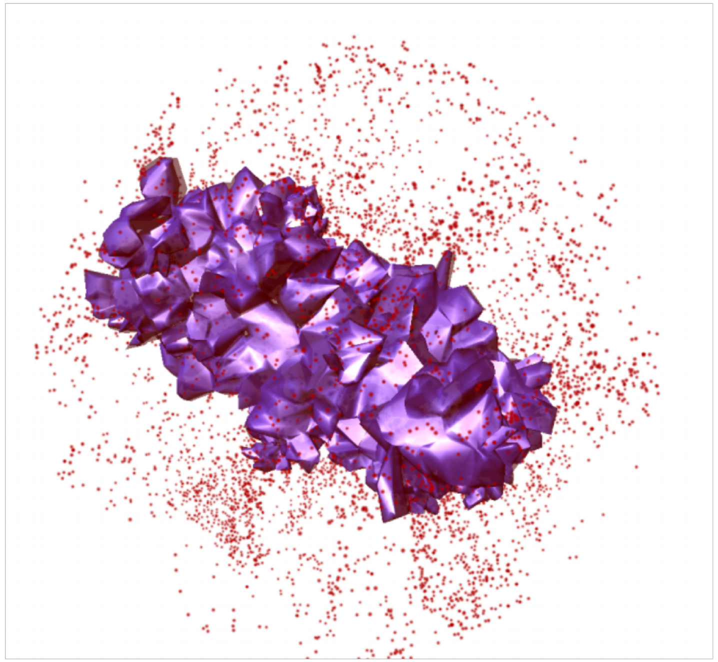
- Void Finding (largely inspired from Alice Pisani's courses)
- **Testing cosmology with voids**

COSMOLOGY WITH VOIDS

A void → Is empty (-ish) ! → its evolution is not ruled by gravity…



(Sutter, 2012b)

In a ΛCDM scenario :

The evolution of a void & its properties should be more sensitive to dark energy !

In a no- Λ scenario (Modified Gravity) :

After the last cosmological observation, we expect gravity to be modified at very large scales in a low density regime environment !

COSMOLOGICAL PROBES WITH VOIDS

A void in itself is just a tool. But, combined with a specific approach, it can become a very efficient probe !

Most of the cosmological probes that applies to galaxies apply to voids as well ! 👍

VOIDS + **BAO**, **AP TEST**, **Lensing**, **RSD**, **Abundance**, **iSW** = **Several different ways to Test cosmology ! (among others)**

The Alcock-Paczynski test

- AP test relies on knowledge of the shape of an object in real space (**ideally with symmetry properties**)

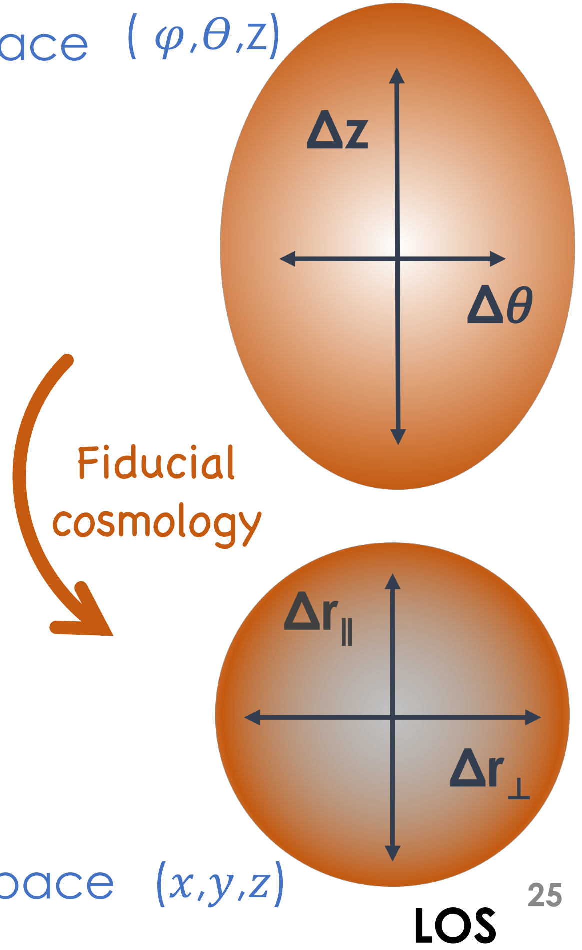
- It investigates the relations between the proportions in Observable Space & in Real space

(Alcock & Paczynksi ,1979)

$$\Delta r_{\perp} = D_A(z)\Delta\theta$$

=

$$\Delta r_{\parallel} = \frac{c\Delta z}{H(z)}$$



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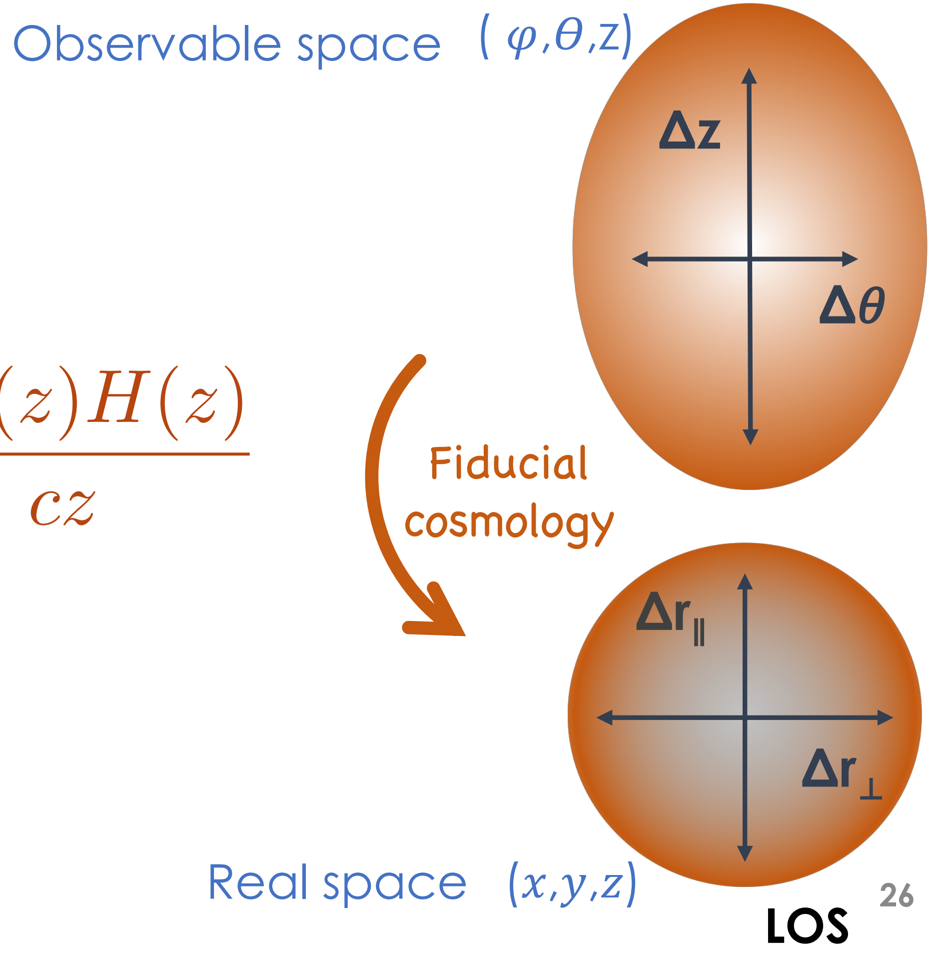
(Alcock & Paczynksi , 1979)

$$\frac{\Delta z}{z\Delta\theta} = \frac{D_A(z)H(z)}{cz}$$



The Alcock-Paczynski test

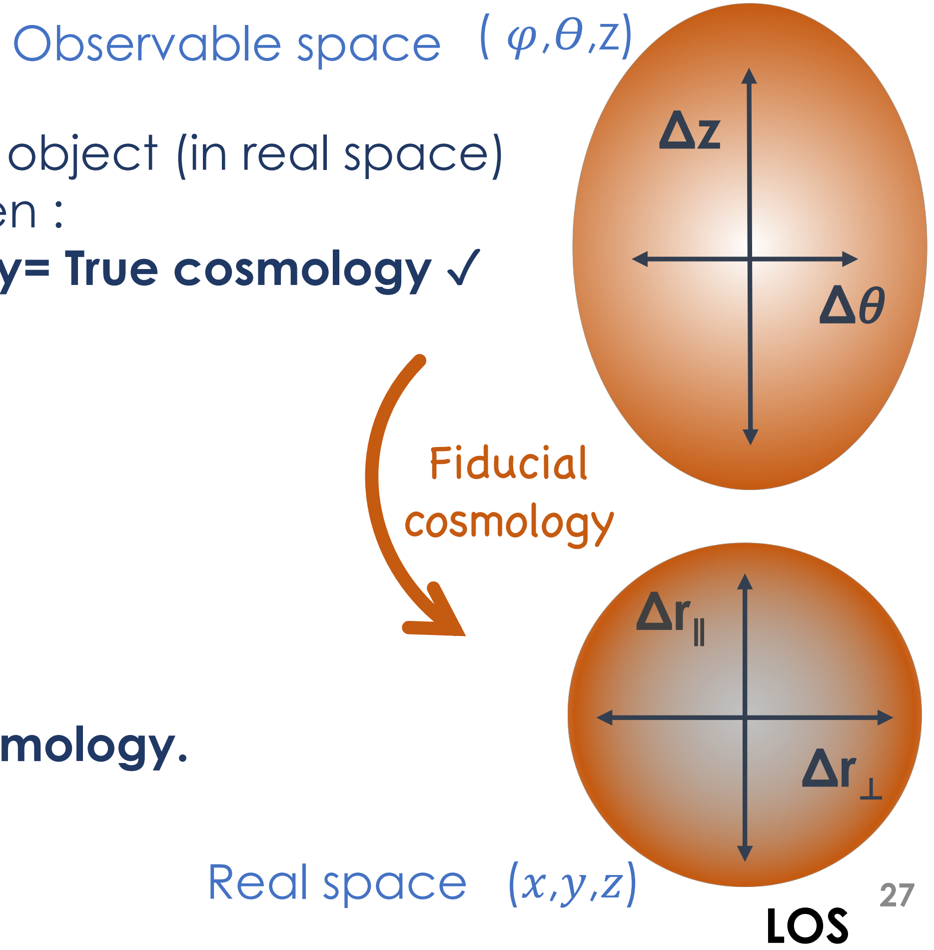
- AP test relies on knowledge of the shape of an object in real space (**ideally with symmetry properties**)

- It investigates the relations between the proportions in Observable Space & in Real space

Iteratively, we are able to deduce information on cosmology.

If the shape of the object (in real space) is as expected, then :
Fiducial cosmology= True cosmology ✓

else,
Wrong fiducial cosmology.



The Alcock-Paczynski Test

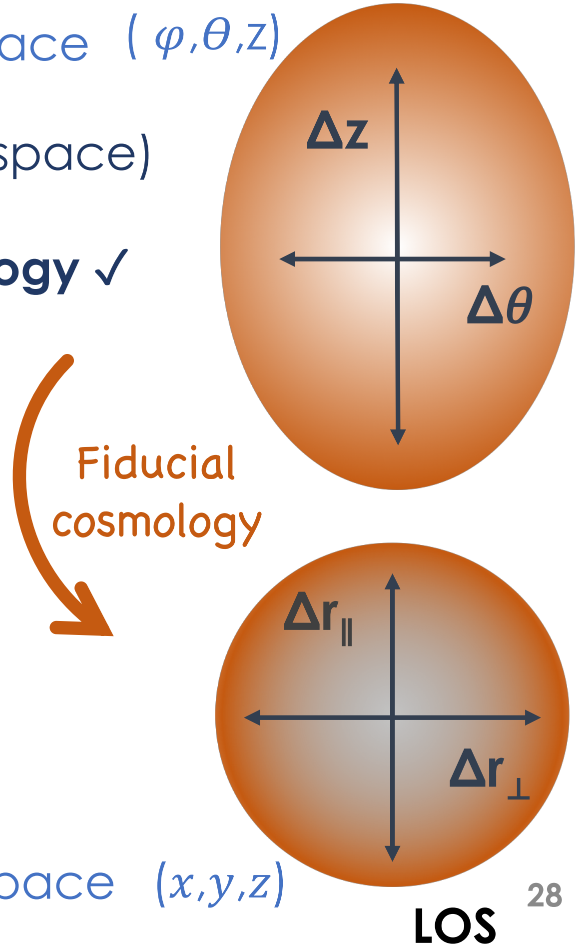
- AP test relies on knowledge of the shape of an object in real space (**ideally with symmetry properties**)

- It investigates the relations between the proportions in Observable Space & in Real space

Can voids be considered as standard object ?

Observable space (φ, θ, z)

If the shape of the object (in real space) is as expected, then :
Fiducial cosmology= True cosmology ✓



else,
Wrong fiducial cosmology.

Real space (x, y, z)

Standard objects

- There are several standard objects useful in cosmology :

BAO peak
(see Pierros Ntelis' talk)

A standard ruler

Voids ?

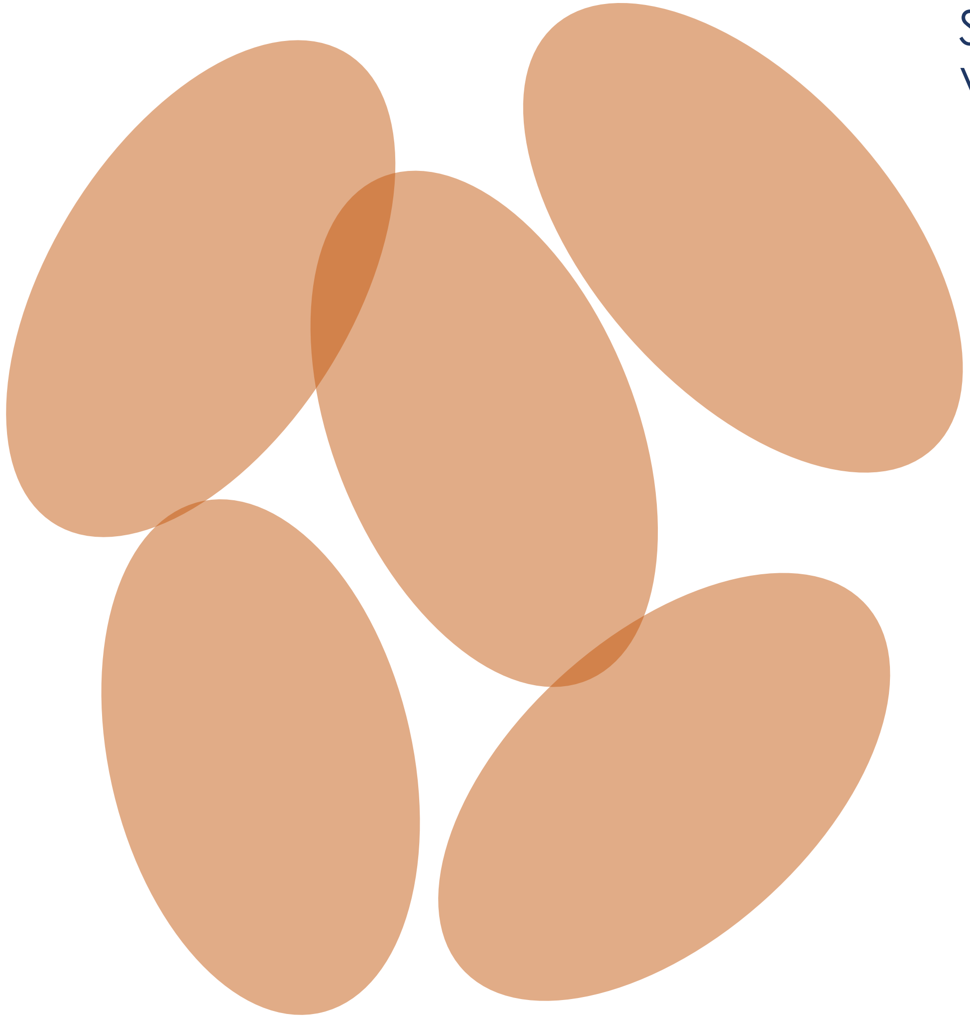
Standard spheres ?

SN 1a
(see Dominique Fouchez's class)

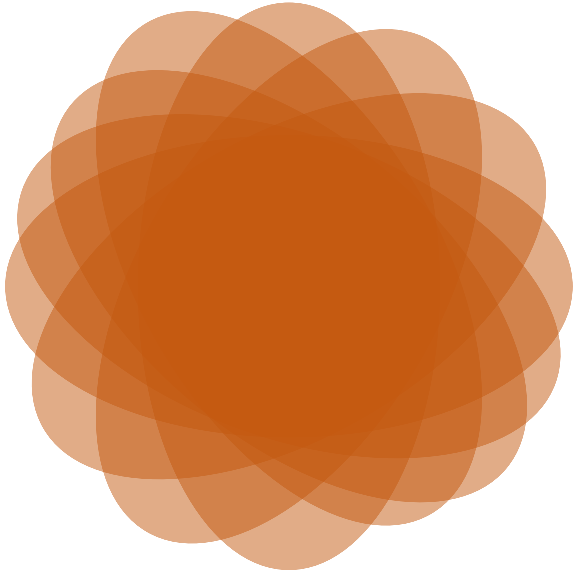
A standard Candle

Void**s** : a standard sphere

Some
Voids



Cosmological Principle



Stacking a large number of voids allows us to obtain a standard sphere.

(Lavaux & Wandelt , 2012)

Voids can be considered as standard objects, **statistically**

Is the application of the AP Test so simple ?

- If you consider the voids to be static, then yes. **But voids are not exempted from dynamical effects !**

- The observed redshift has two kind of contributions :

$$z_{meas} = z_c + \frac{v_{pec}\cos\theta}{c}$$

Cosmological contributions

Leads to cosmological distortions that we probe with AP

Peculiar velocities contributions

Finger of God Effect

Kaiser Effect

Redshift-Space Distortions

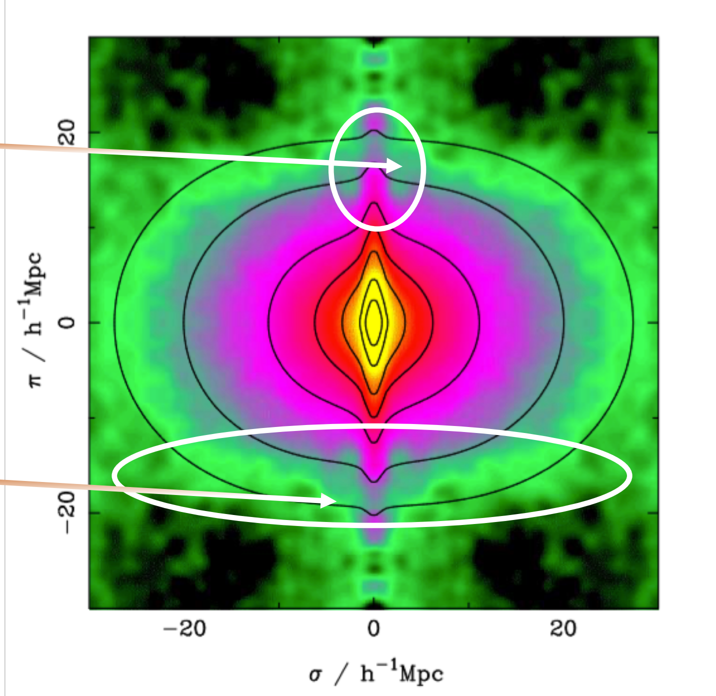
Peculiar types of velocities

- Redshift Space Distortions caused by **peculiar velocities** of galaxies have 2 scale dependents effects on the observations (and on voids too !)

On small scales : Random velocities !
→ Elongation along the LOS : Finger of God effect

On large scales : Coherent infall velocities
→ Flattening along the LOS : Kaiser Effect

Radial Separation (LOS)



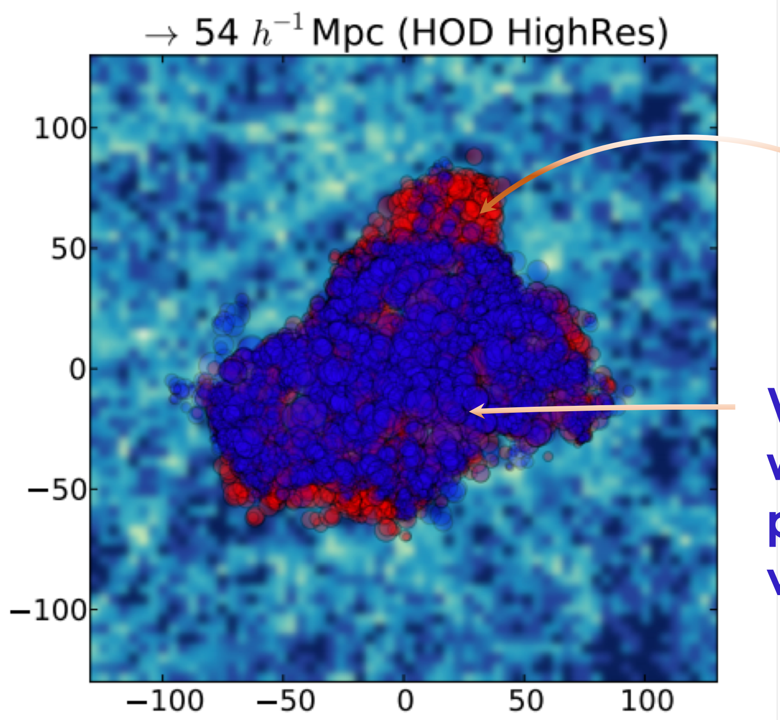
(Peacock 2001) Transverse Separation

Peculiar Velocities (especially random) are the main source of systematics in Cosmology

Minimizing the effects of peculiar velocities !

Tests on simulation were done to study the effects of peculiar velocities on the void definition.

As a result : peculiar velocities tend to enhance the shape of the structure.

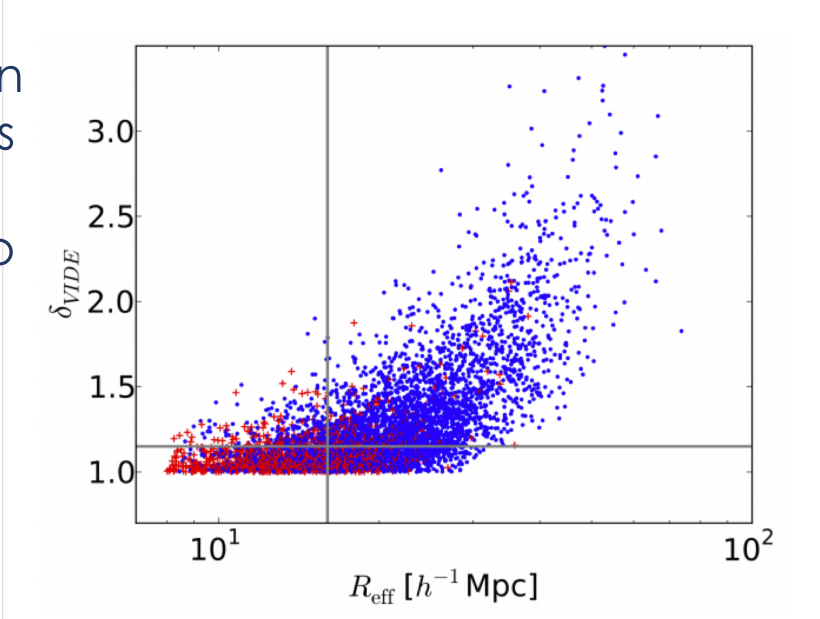


Voids with peculiar velocities

Voids without peculiar velocities

Finding match between the two catalogs allows us to find different cuts enhancing the signal to noise ration

Small voids are more affected by the peculiar velocities



(Pisani et al 2015 , arxiv:1506.07982)

Application of the AP Test

- B. Ryden was the first to suggest voids as an appropriate object to apply the AP Test (*Ryden 1995*).

- Measuring the extent of the void in the direction of LOS ($\mathbf{r}_{\|}$) & in the transverse direction to the LOS ($\mathbf{r}_{\perp}$), we can extract the void stretch :

$$e_v(z) := \frac{\Delta z}{z\Delta\theta} = \frac{D_A(z)H(z)}{cz}$$

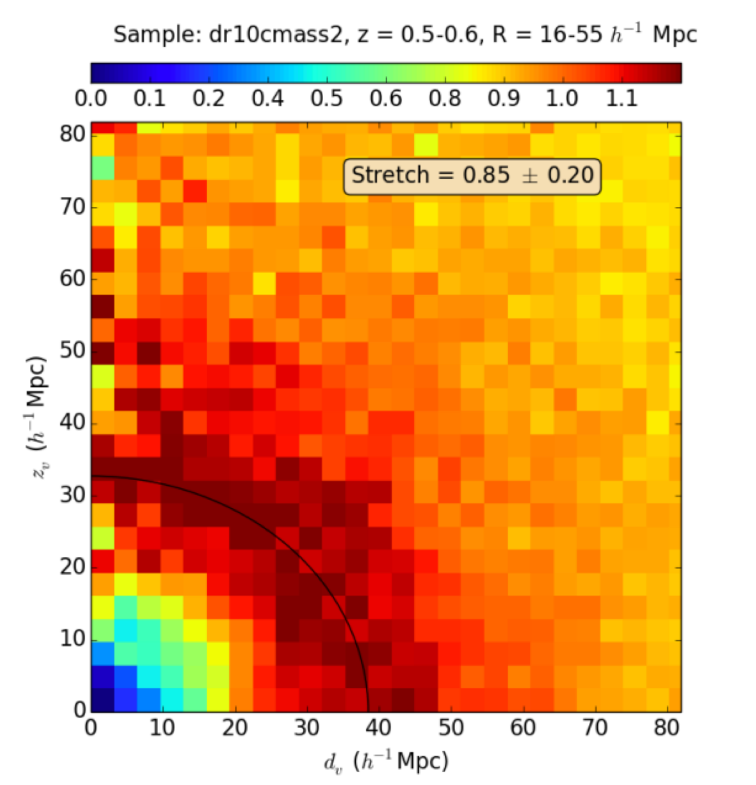
In a Flat Universe :

$$D_A(z) = \frac{1}{1+z}\int_0^z \frac{cdz}{H(z)}$$

&

$$\Omega_\Lambda = 1 - \Omega_m$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$



DR10 voids stack, *Sutter 2014*

Application of the AP Test

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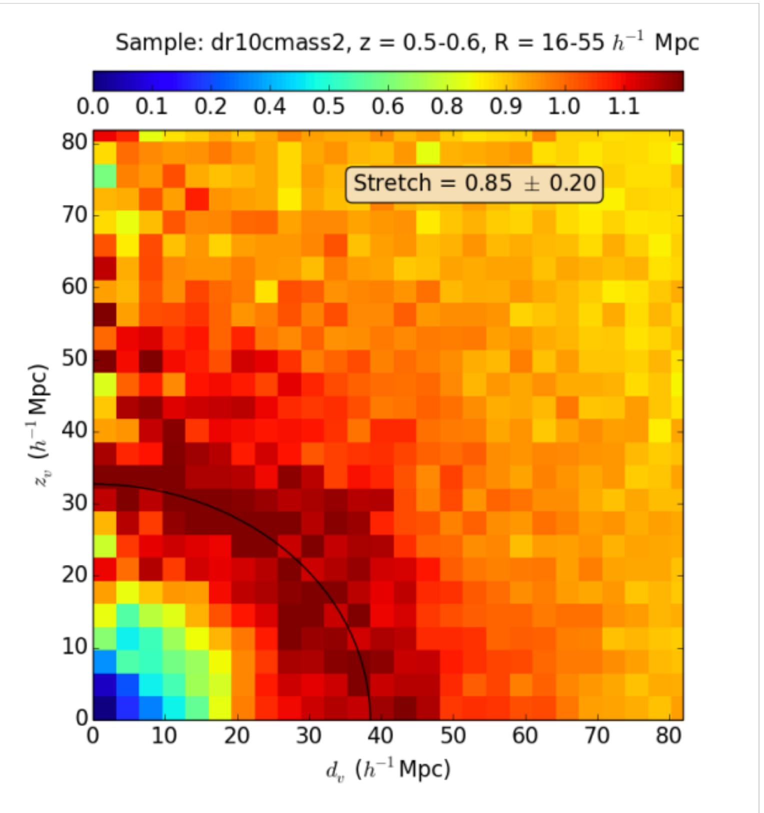
- Measuring the extent of the void in the direction of LOS ($\mathbf{r}_{\parallel}$) & in the transverse direction to the LOS ($\mathbf{r}_{\perp}$), we can extract the void stretch :

$$e_v(z) := \frac{\Delta z}{z\Delta\theta} = \frac{D_A(z)H(z)}{cz}$$

Most recent constraint on Ω_m from (*Mao et al. 2017*) :

$$\Omega_m = 0.38^{+0.18}_{-0.15}$$



DR10 voids stack, *Sutter 2014*

Investigating Redshift Space Distortions around voids

- Not all of the effects of peculiar velocities are un-interesting ! Some of them give us information on the formation of the Large Scale Structure!

- **Kaiser Effect** is actually very interesting to us because it shows the mouvement of galaxies toward a gravitationnal potential.

- It carries information about the evolution of the structures that we observe.

- Now that we know that we can enhance the signal to noise ratio of our voids through a cut on the size of the voids, we can investigate the **evolution of the large scale structure.**

How do we measure that ?

The growth rate of structures

- Perturbation theory describes the evolution in time of the primordial density fluctuations.

- The density contrast δ is defined as the deviation in density with respect to the average density of matter in the univers $\bar{\rho}$.

$$\delta(r) = \frac{\rho(r) - \rho(\bar{r})}{\rho(\bar{r})}$$

- The evolution δ of is given by the growth rate of structure : $f = \frac{d\ln\delta}{d\ln a} \approx \Omega_m(z)^\gamma$

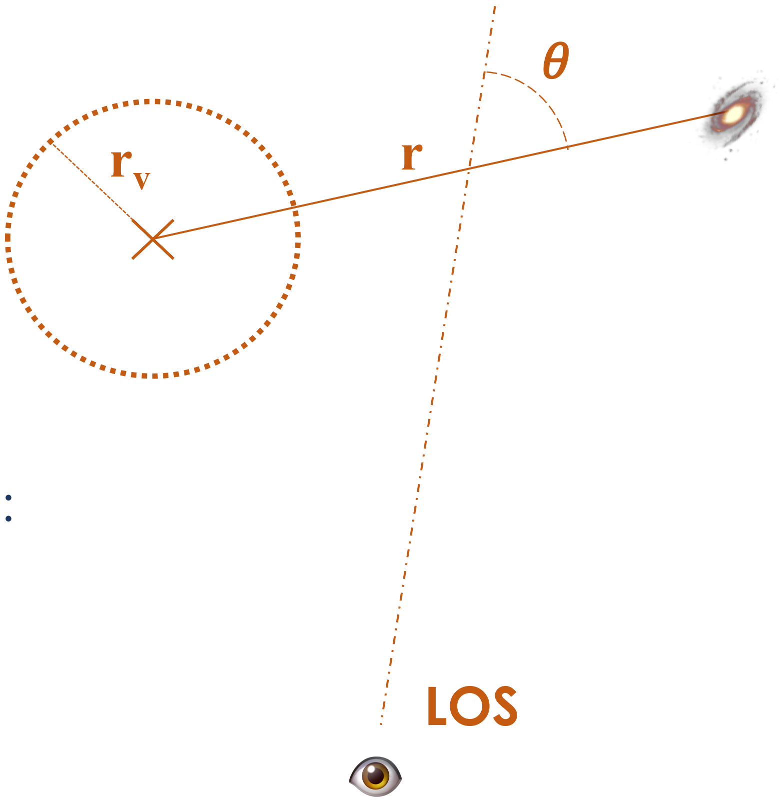
In the framework of General Relativity , γ is predicted : $\gamma \approx 0.55$

Void-Galaxy correlation function

The distribution of the galaxies around voids is easily conceivable : they cluster at the boundary of the void creating the filaments in the cosmic web.

To quantify this, we measure the cross-correlation between void and galaxies :

- The excess probability to find a galaxy within a radius **r** from the **center** of the void in regard to a uniform random distribution of galaxies.



The density contrast is computed through the following estimator :

$$\delta_{vg} = \xi_{vg}(s,\mu) = D_v D_g(s,\mu) - D_v R_g(s,\mu)$$

Where : $\mu = \cos\theta$ and $s = \frac{r}{r_v}$

Decomposition in Legendre Polynomials

Due to RSD, the correlation function is anisotropic. we can decompose it in Legendre Polynomials :

$$\xi_0 = \int_0^1 \xi(s,\mu) d\mu$$

$$\xi_2 = 5 \int_0^1 \frac{3\mu^2 - 1}{2} \xi(s,\mu) d\mu$$

The only non zero components are the monopole and the quadrupole. (Hamilton 1992, 1997)

The monopole marginalize the correlation function in μ and contains the information along the line of sight : namely the **density profile of the void in redshift space**

The quadrupole contains the information on **the fluctuations of density caused by the dynamics of the galaxies around the void.**

Multipole Analysis

The monopole and the quadrupole are **linked to the real-space correlation function** as such (Cai et al 2016) :

$$\xi_0 - \bar{\xi_0} = (1 + \frac{\beta}{3})[\xi(\mathbf{s}) - \bar{\xi}(\mathbf{s})]$$

$$\xi_2 = \frac{2\beta}{3}[\xi(\mathbf{s}) - \bar{\xi}(\mathbf{s})]$$

Where $\bar{\xi}(s) = \frac{3}{s^3}\int_0^s \xi(s')s'^2 ds'$

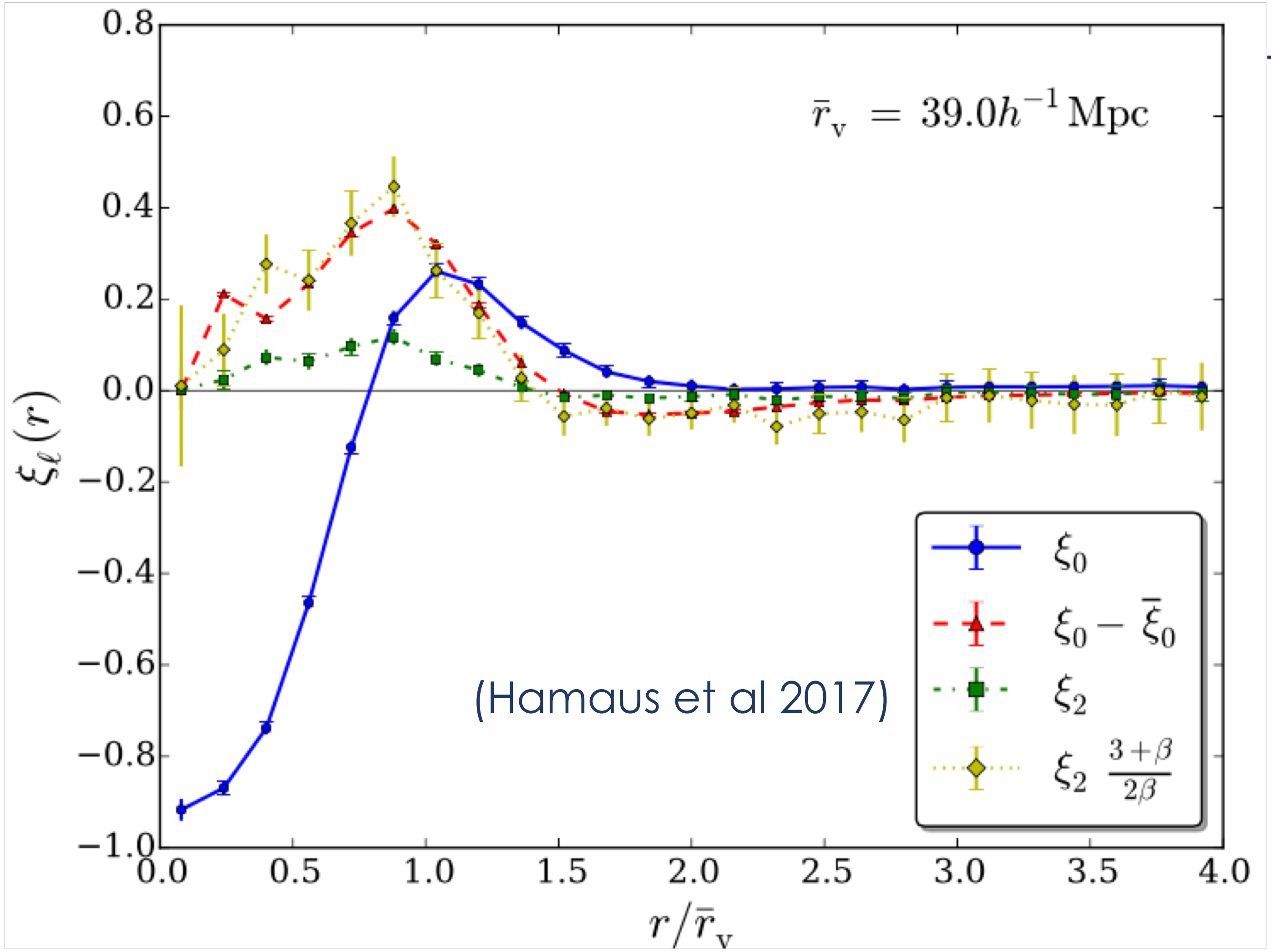
The appearance of β is a really good thing because :

$$\beta = \frac{f}{b} = \frac{(\Omega_m)^\gamma}{b}$$

b is the galaxy bias. Indeed , the galaxies do not represent the whole distribution of matter.

The most used assumption is that this bias is linear : $\delta_{gal} = b\delta_m$

Multipole of the void-galaxy correlation function



The ratio yields : $\frac{\xi_2}{\xi_0 - \bar{\xi}_0} = \frac{2\beta}{3+\beta}$

A constant !

Applied BOSS DR12 CMASS galaxies :

$$\beta = 0.455^{+0.056}_{-0.054}$$

Which is consistent with General Relativity & Lambda CDM :

$$\beta = 0.416$$

and competitive with regular RSD constraints !

$$\beta = 0.435 \pm 0.070$$

(Chuang et al 2016)

Investigating the number of voids

- The evolution & formation of large scale structure is highly dependent on the acceleration of the expansion of the Universe : dark energy & its equation of state.

- Understanding how such structures comes to be allows us :

To predict the number of voids **for a given cosmology**

To constraint cosmology **for a given number of voids**

Counting the void to probe dark energy

- Sheth & Van de Weygaert (2004) proposed a theory of void evolution & hierarchy called the set excursion model which highlights 3 void evolution process :

→ **Void-in-void**	Several subvoids are embedded in a larger void
→ **Cloud-in-void**	Some cluster are present in a large underdensity zone
→ **Void-in-Cloud**	An underdensity is embedded in a cluster of galaxies

- This theory allows to predict the number of void in terms of Radius for 2 kinds for the Void-in-Void & Cloud-in-void case.

Counting the void to probe dark energy

Sheth & Van de Weygaert (2004) proposed a theory of void evolution & hierarchy.

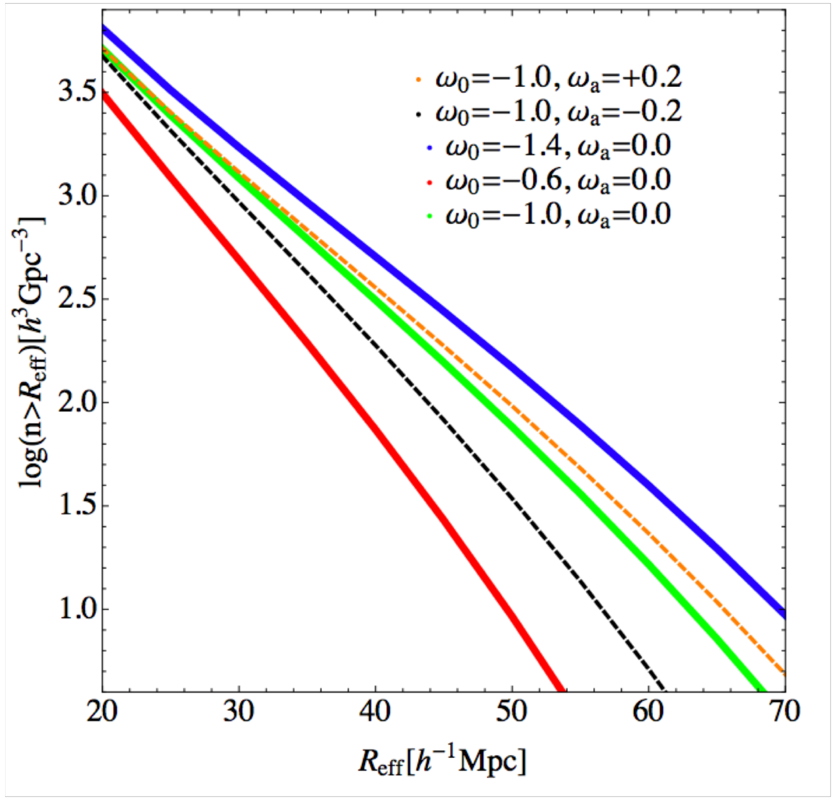
Counting the number of voids depending on the radius can give us information about the dark energy equation of state.

In Lambda CDM, the equation of state of dark energy is constant, $w = -1$

Measuring this w in a precise manner would allow us to determine the underlying physics behind the accelation of the expansion of the Universe.

Is it a constant ? Or, a time varying quantity ?:

$$w = w_0 + w_a \frac{z}{1+z}$$



Alice Pisani, Cosmology with cosmic voids, Université Pierre et Marie Curie - Paris VI, 2014.

Estimating the number of voids in future surveys

- It is also possible, for a given cosmology to infer the number of voids likley to be measured in future surveys.

- A bit like a recipe , you need → A cosmology , e.g. Lambda CDM (Planck) cosmology, the survey features (number of galaxies, redshift etc etc) & a simulation adapted to the survey features !

- Combined with the excursion model, the number of voids expected for WFIRST & euclid are :

50 millions galaxies in euclid

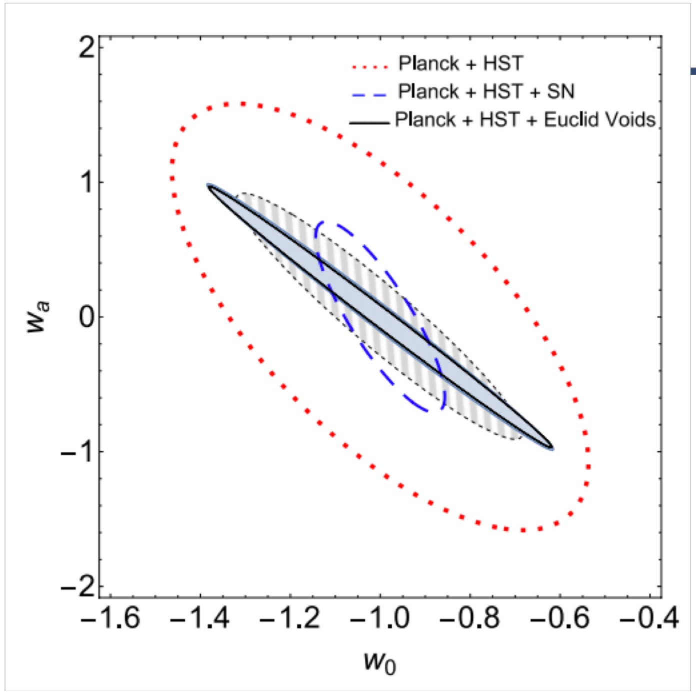
20 millions galaxies in WFIRST

250 000 voids in WFIRST

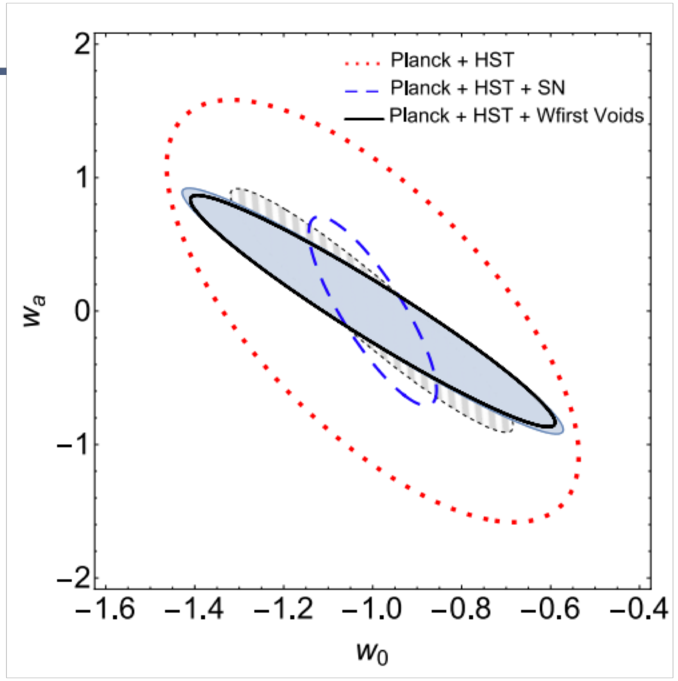
780 000 voids in euclid

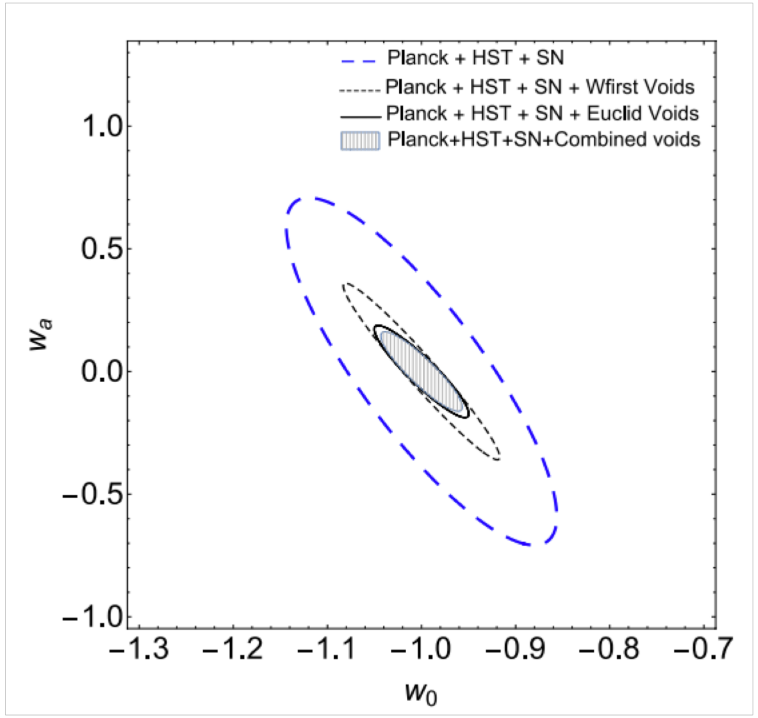
(Pisani et al. 2015)

Forecast for future surveys with void abundance



Constraints on dark energy equation of state are expected to be tighter





(Pisani et al. 2015)

Other voids probes

- There are other void probes that I mentionned :

iSW effect :

If a photon passes through a low density zone (a void !) as the universe expands in an accelerated manner : its energy is slighly modified !

(Granett et al. 2008, Ilic et al. 2012)

Lensing :

Problem : it is photometric.

Sanchez et al. 2016, confirmed that voids are truly underdense

→ Agreement between spectroscopy & photometry !

BAO peak :

Voids also present the BAO peak feature & can provide tighter constraint combined with the constraint obtained from galaxy

(Kitaura et al. 2016 ,)

What have we learned today ?

Dark Energy **is still a mystery** to us all but we are working on it !

New prospects are coming up with the high statistics provided by :

- euclid
- WFIRST
- DESI

We'll be able to probe at higher redshift !

Voids are new tools to constraint cosmology.

Combined with different method , they can give different jnformation on cosmology

- Modified Gravity
- Content Of the Universe
- Dark Energy equation of state

Whatever the probe used :

You have to be mindful of the systematic effects in your measurement.

For example : The effect caused by the dynamics of galaxies in clustering.